Claims

1. A device to regulate current provided to a permanent magnet (PM) machine responsive to a plurality of phase current signals to produce torque on a shaft comprising:

a processing and drive circuit responsive to a direct voltage command signal and a quadrature voltage command signal, said processing and drive circuit configured to produce said plurality of phase current signals for input to said permanent magnet machine;

a current regulator including,

a command circuit responsive to a torque input command signal configured to produce a direct current command signal and a quadrature current command signal;

a control circuit responsive to the direct and quadrature current command signals configured to produce said direct and quadrature voltage command signals; and

a limiter configured to limit the direct and quadrature voltage command signals to a preselected level.

2. The device of claim 1 wherein said command circuit includes a D-axis current command circuit responsive to a torque command, one of (i) a zero time vector command, (ii) a time for voltage vector or (iii) a voltage magnitude configured to produce said direct current command signal.

3. The device of claim 1 further including a transform circuit responsive to said phase current signals and an angular position of said shaft configured to produce a direct synchronous current feedback signal Idsf and a quadrature synchronous current feedback signal Iqsf.

4. The device of claim 3 wherein said command circuit further includes a Q-axis current command circuit responsive to a torque command, and said direct synchronous current feedback signal configured to produce said quadrature current command signal.

5. The device of claim 1 wherein said control circuit includes said limiter and comprises at least a pair of clamps for respectively limiting the direct and quadrature voltage command signals Vds and Vqs generated by the control circuit.

6. The device of claim 5 wherein the command circuit includes a D-axis current command circuit for producing said direct current command signal and a Q-axis current command circuit, for producing said quadrature current command signal, the control circuit including a D-axis control circuit responsive to said direct current command signal and a Q-axis control circuit responsive to said quadrature current command signal, one of said pair of clamps being in said D-axis control circuit and the other one of said pair of clamps being a said Q-axis control circuit.

7. The device of claim 6 wherein said control circuit having a first portion corresponding to said D-axis control circuit and a second portion corresponding to said Q-axis control circuit, wherein said first portion includes a first pathway having a first proportional gain, a second pathway having a first integrator and a first clamp, and a third pathway having a first summing node and a second clamp, and wherein said second portion includes a fourth pathway having a second proportional gain, a fifth pathway having a second integrator and a third clamp, and a sixth pathway having a second summing node and a fourth clamp said second and fourth clamps defining said limiter, said pair of clamps being included in said first, second, third and fourth clamps.

8. The device of claim 7 wherein said first pathway is between a first tapping node and said first summing node, said second pathway disposed between said first tapping node and said first summing node, said fourth pathway between a second tapping node and said second summing node, said fifth pathway between said second tapping node and said second summing node.

9. The device of claim 6 wherein said D-axis control circuit produces said direct voltage command signal, and one of said pair of clamps limit said direct voltage signal in accordance with the following:

$$-Vmag^* \leq Vds \leq Vmag^*$$

10. The device of claim 6 wherein said Q-axis control circuit produces said quadrature voltage command signal, and the other one of said pair of clamps limit said quadrature voltage signal in accordance with the following in a motoring mode:

$$MIN \leq Vqs \leq \left\lfloor \sqrt{Vmag^{*2} - Vds^{2}} \right\rfloor * K .$$

11. The device of claim 6 wherein said Q-axis control circuit produces said quadrature voltage command signal, and the other one of said pair of clamps limit said quadrature voltage signal in accordance with the following in a generating mode:

$$MIN \leq Vqs \leq Vmag * K .$$

12. The device of claim 1 wherein said limiter is operative to limit said direct and quadrature voltage command signals Vds and Vqs as follows:

Vds = -Vmag* [sin(Delta Maximum)],

Vqs = Vmag* [cos(Delta Maximum)],

Where Delta is greater than Delta Maximum and where Delta is defined as follows:

Delta = arctan(-Vds/Vqs) and

where Delta must be within the following range:

Delta Minimum ≤ Delta ≤ Delta Maximum.

13. The device of claim 1 wherein said limiter is operative to limit said direct and quadrature voltage command signals Vds and Vqs as follows:

Vds = -Vmag* [sin(Delta Minimum]

Vqs = Vmag* [cos(Delta Minimum)]

Where Delta is less than Delta Minimum, and where Delta is defined as follows;

Delta = arctan(-Vds/Vqs) and

where Delta must be in within the following range:

Delta Minimum ≤ Delta ≤ Delta Maximum.

14. The device of claim 1 wherein a direct current error signal Iderror is produced by subtracting a direct synchronous current feedback signal Idsf from said direct current command signal Ids*, and wherein a quadrature current error signal Iqerror is produced by subtracting a quadrature synchronous current feedback signal Iqsf from said quadrature current command signal Iqs*.

15. The device of claim 2 wherein said D-axis current command circuit includes a proportional integrator block responsive to (i) at least one of a zero time vector error signal feedback $T0_f$, a time for voltage vector (T1+T2), or a voltage magnitude Vmag, and (ii) at least one of said zero time vector command T0*, a time for voltage vector command (T1+T2)* or a voltage magnitude command Vmag*, for producing an output, and a fifth limiter responsive to the output for producing a D-axis time zero signal, IdsT0, no larger than a second preselected level; a maximum torque per ampere circuit for producing a D-axis current look up table signal, IdsLUT as function of TORQUE*; a summing circuit responsive to the D-axis time zero signal and the D-axis current look up table signal to produce a D-axis current command Ids*.

16. A method for regulating current provided to a permanent magnet (PM) machine that is responsive to a plurality of phase current signals to produce torque on a shaft, said method comprising the steps of:

providing a processing and drive circuit responsive to a direct voltage command signal and a quadrature voltage command signal, said processing and drive circuit configured to produce said plurality of phase current signals for input to said permanent magnet machine;

providing a current regulator including (i) a command circuit responsive to a current input command signal configured to produce a direct current command signal and a quadrature current command signal, and (ii) a control circuit responsive to the direct and quadrature current command signals configured to produce said direct and quadrature voltage command signals; and

clamping the output of the current regulator so as to prevent the current regulator from exceeding its output voltage limit to thereby maintain control of said machine.

17. The method of claim 16 wherein said clamping step includes the substeps of:

clamping the direct voltages command signal Vds using a first clamp to a first preselected level; and

clamping the quadrature voltage command signal Vqs using a second clamp to a second preselected level.

18. The method of claim 17 wherein each of said clamping substeps include the further step of:

clamping respective transient and steady-state components of the direct voltage command signal Vds and quadrature voltage command signal Vqs.